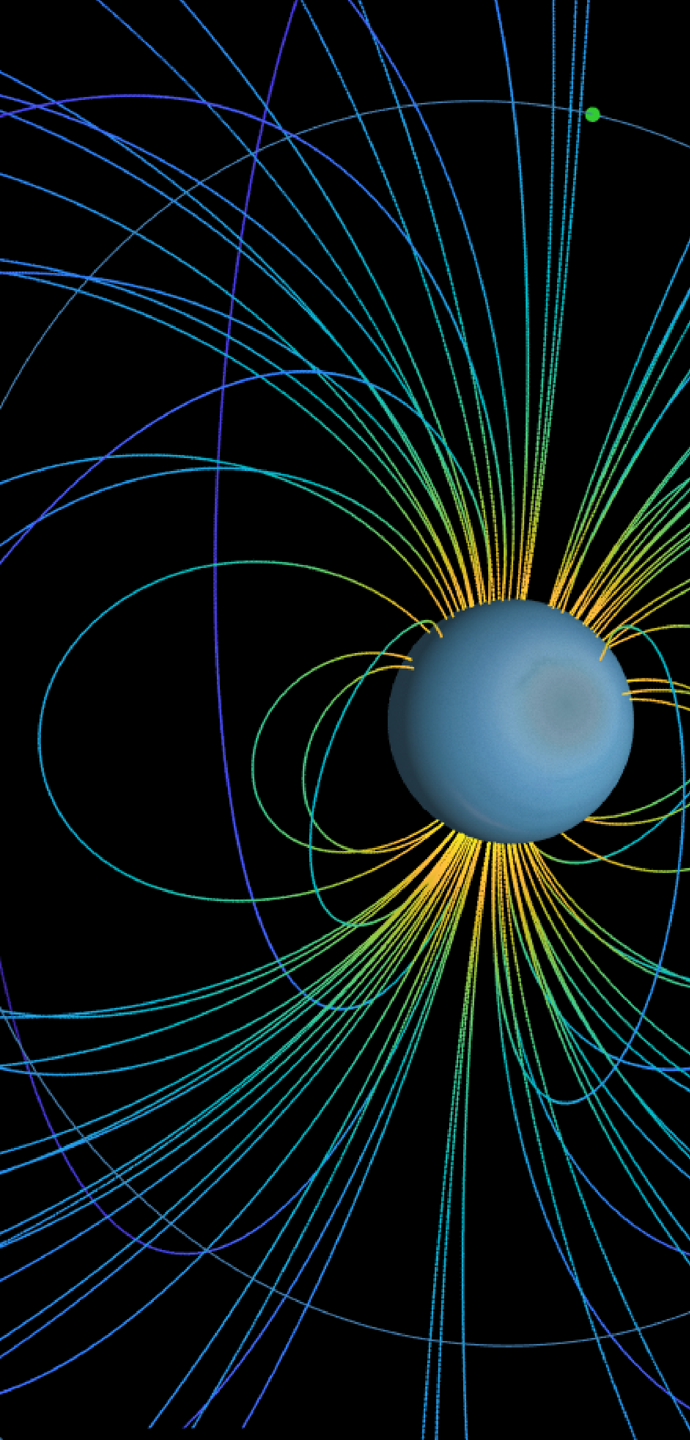

In Search of Subsurface Oceans within the Moons of Uranus

LPSC 2021, #1559

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What Voyager 2 Told Us About Uranus

Only visitor was Voyager 2 on January 24 1986

Uranus:

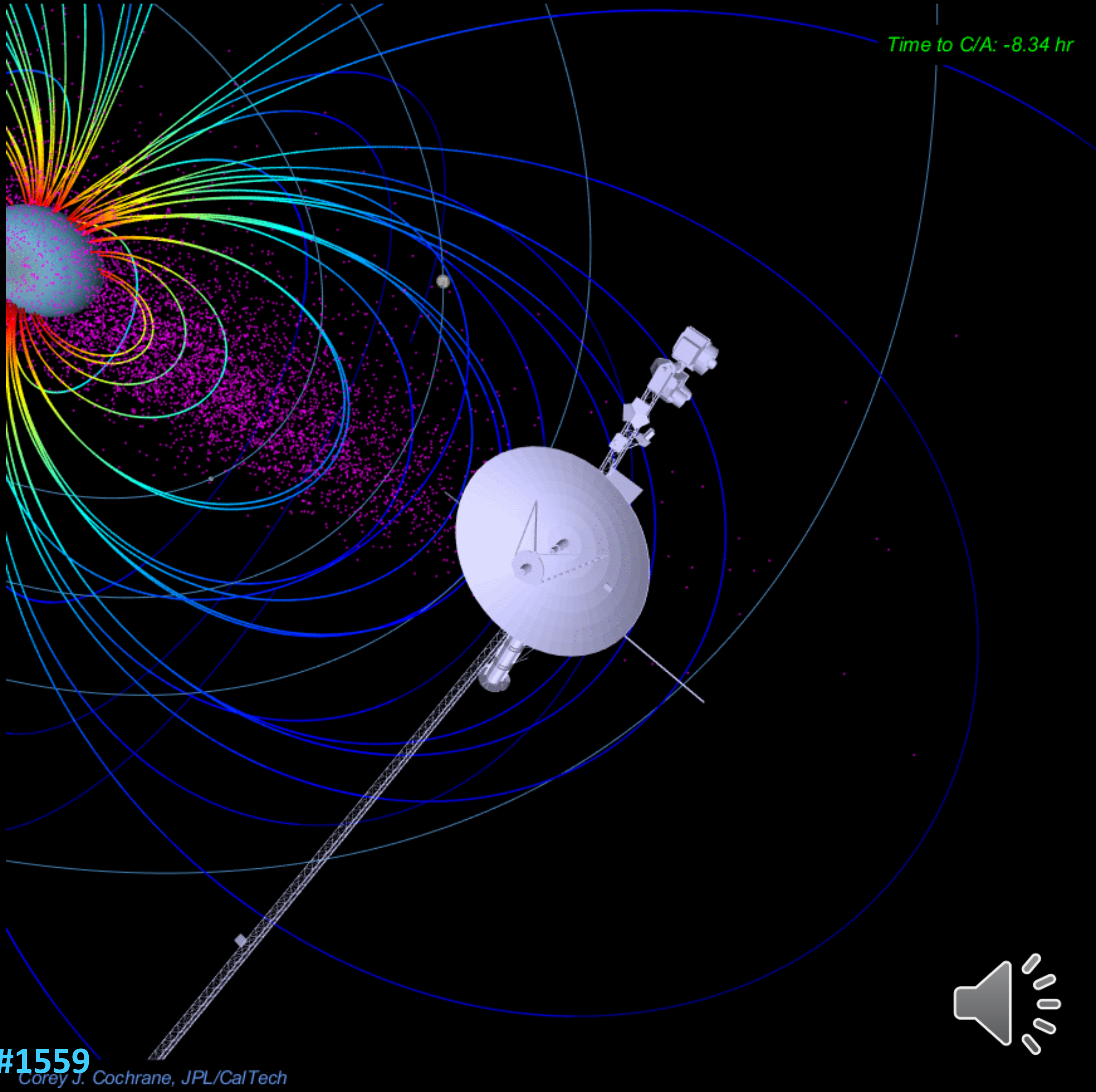
- Roughly 3.9 x larger than Earth (by diameter, 25,000km)
- Spins on it's side (98^o, likely from a large impact
- Composition: Hydrogen, Helium, Methane (rocky core)
- Has a ring system made of rock, dust, and ice

Moons:

- Discovery of 10 new moons (and two rings)
- Revealing images of Miranda, Ariel, Umbriel, Titania, and Oberon

Magnetic Properties

- Magnetic Moment: 3.9×10^{17} T·m^3 (50x stronger than Earth's), surface field roughly the same
- Magnetic axis tilted relative to rotational axis by 59^o



What Makes the Uranus System So Special

Strong magnetic field

- Magnetic Moment: 3.9×10^{17} T·m^3
- 50x stronger than Earth's
- Strong dipolar and quadrupolar character

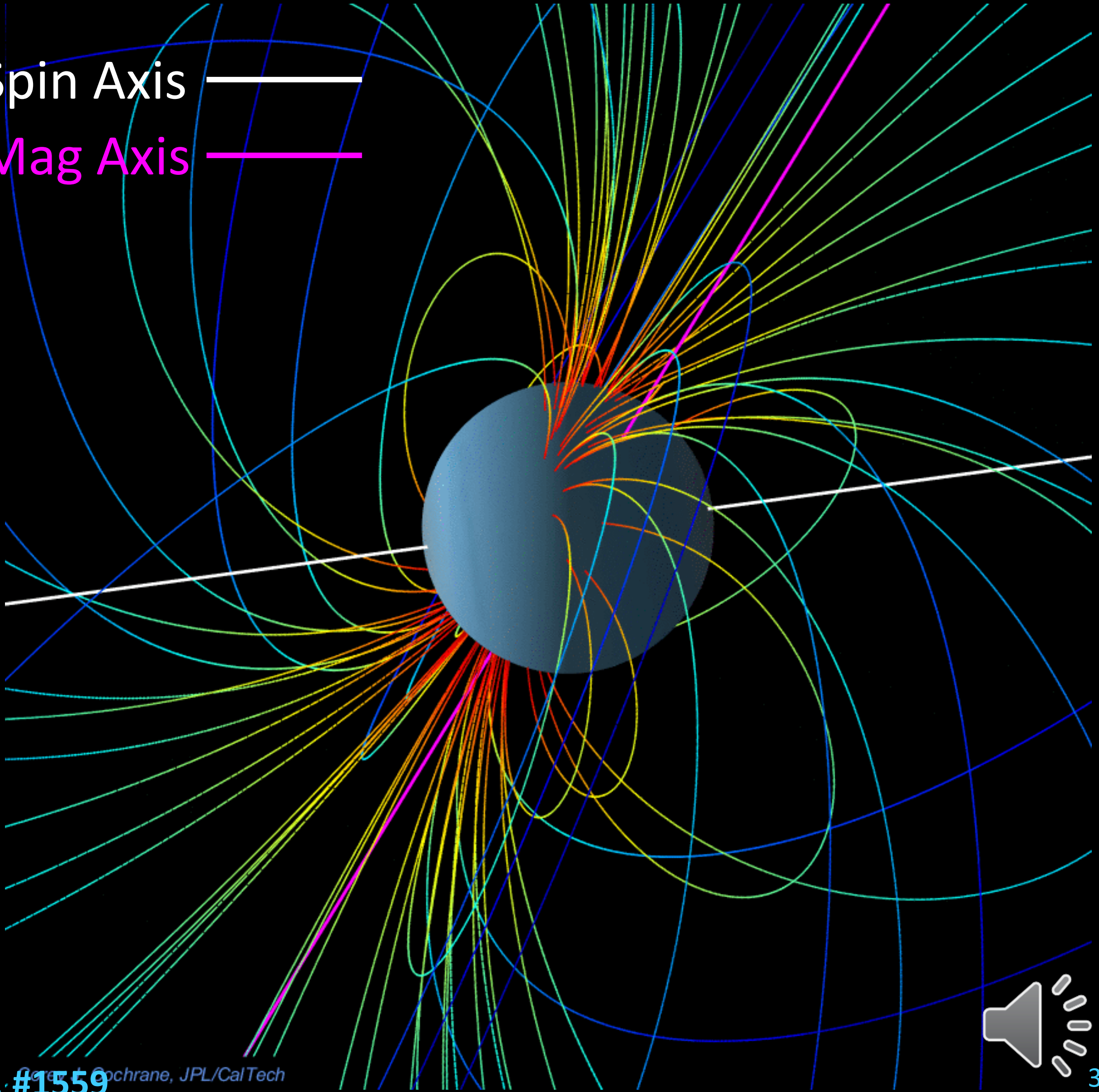
Magnetic axis tilted relative to spin axis by 59^{o}

- Creates large time variation in field at each moon
- Only time-variations in magnetic field induce electrical currents in conductors
- This geometry ensures that moons will be outside of the plasma sheet for most of the time

Orbital Period

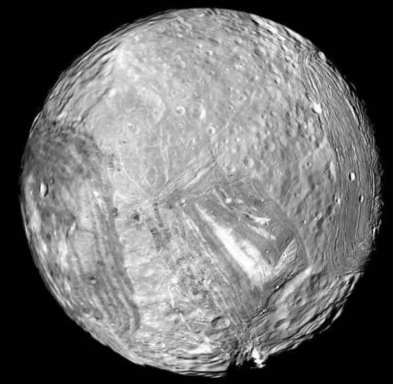
- Slight orbital eccentricity of each of the moons (and large inclination of Miranda) results in orbital waves

J.E.P. Connerney, M.H. Acuna, N.F. Ness, "The Magnetic Field of Uranus", J. Geophysical Research, vol. 92, pp: 15m329-15,336, 1987.
Herbert, F. (2009), Aurora and magnetic field of Uranus, J. Geophys. Res., 114, A11206
Podolak, M.; Weizman, A.; Marley, M. (December 1995). "Comparative models of Uranus and Neptune". Planetary and Space Science. 43 (12): 1517–1522

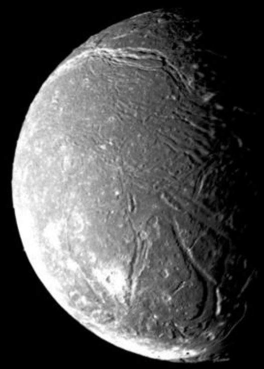


This moons of Uranus and their properties

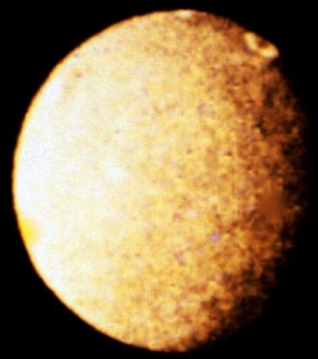
Miranda



Ariel



Umbriel



Titania

Oberon

	Miranda	Ariel	Umbriel	Titania	Oberon
Semi-major axis	129,390 km	191,020 km	266,000 km	435,910 km	583,520 km
radius	235.8 km	578.9 km	584.7 km	788.4 km	761.4
Orbital inclination	4.2^{o}	0.26^{o}	0.13^{o}	0.34^{o}	0.058^{o}
eccentricity	0.0013	0.0012	0.0039	0.0011	0.0014
Orbital period	33.92 hr	60.48 hr	99.46 hr	208.9 hr	323.11 hr
Rotation period	synchronous	synchronous	synchronous	synchronous	synchronous

Why Are These Moons Potential Ocean Worlds?

Images from Voyager 2 suggests that they're made of rock and ices, deep ridges, folds, valleys, faults, deep canyons, steep cliffs, smooth plain

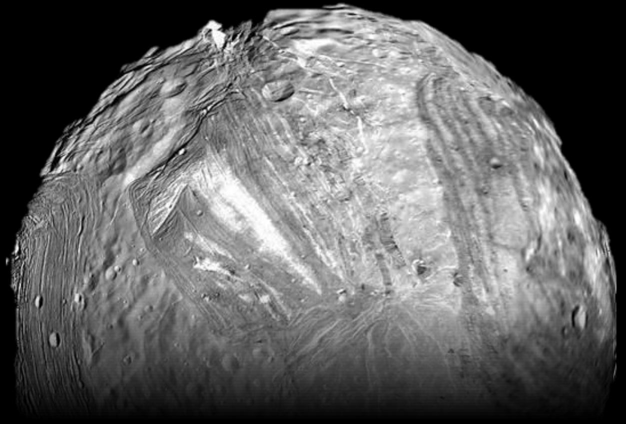
similar features exist on Europa and Enceladus which there is evidence of a subsurface ocean, indicating that these surface features could be created by an ocean

Although small, these moons could potentially harbor water beneath their shells

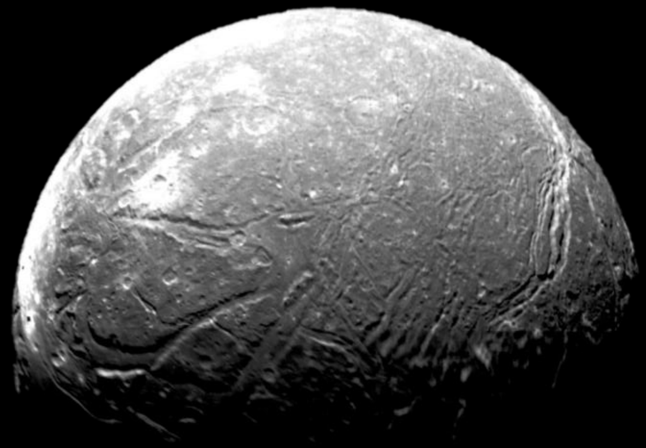
moons are colder, likely to be a thick shell, indicating deeper ocean slightly more difficult to detect

Uranus provides the perfect magnetic environment for magnetic induction investigations at the moons.

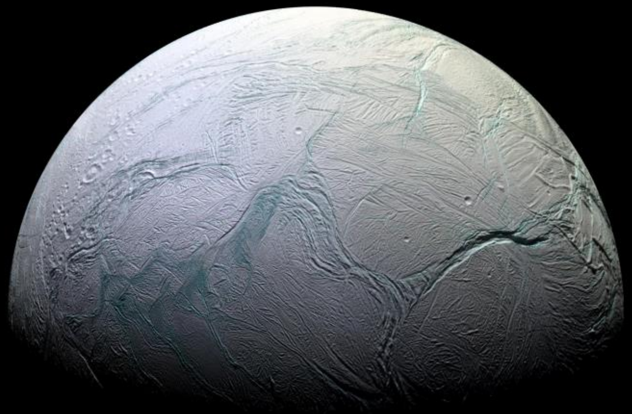
Miranda/Uranus



Ariel/Uranus



Enceladus/Saturn



Europa/Jupiter

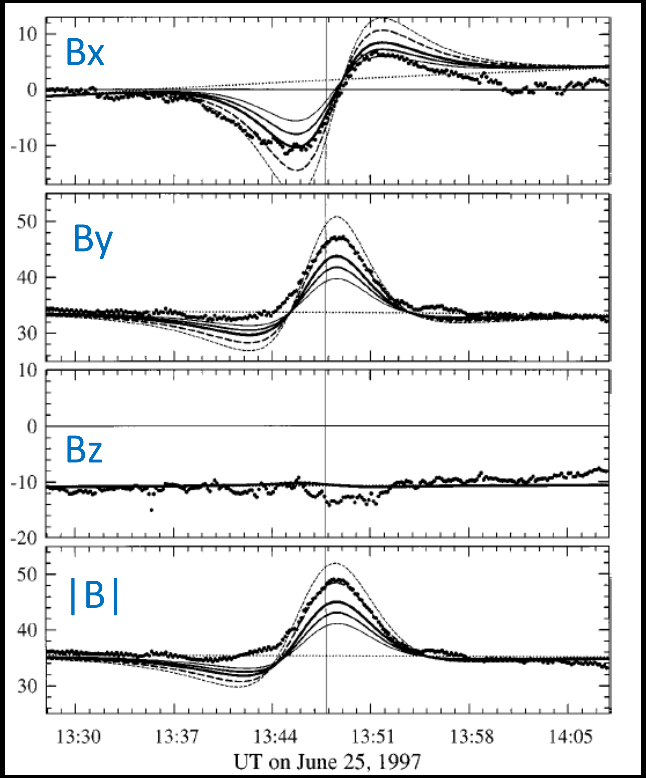
Pioneers of the Magnetic Induction Technique

Global scale ocean magnetic induction response was first proposed by M. Kivelson, K.K. Khurana, et al. explain the data collected by Galileo's magnetometer on the passes of Europa and Callisto.

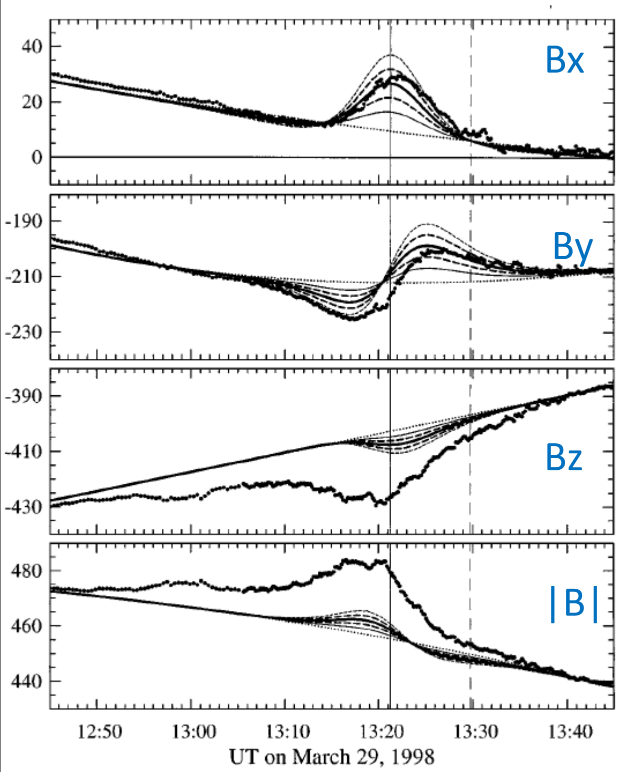
Able to show that the magnetic signature from these moons are synchronized to Jupiter's rotation period

This very exciting result forms the basis of the Europa Clipper Magnetometer (ECM) investigation, now expected to perform near 50ish flybys of Europa and a handful of Callisto.

Callisto C09 Pass



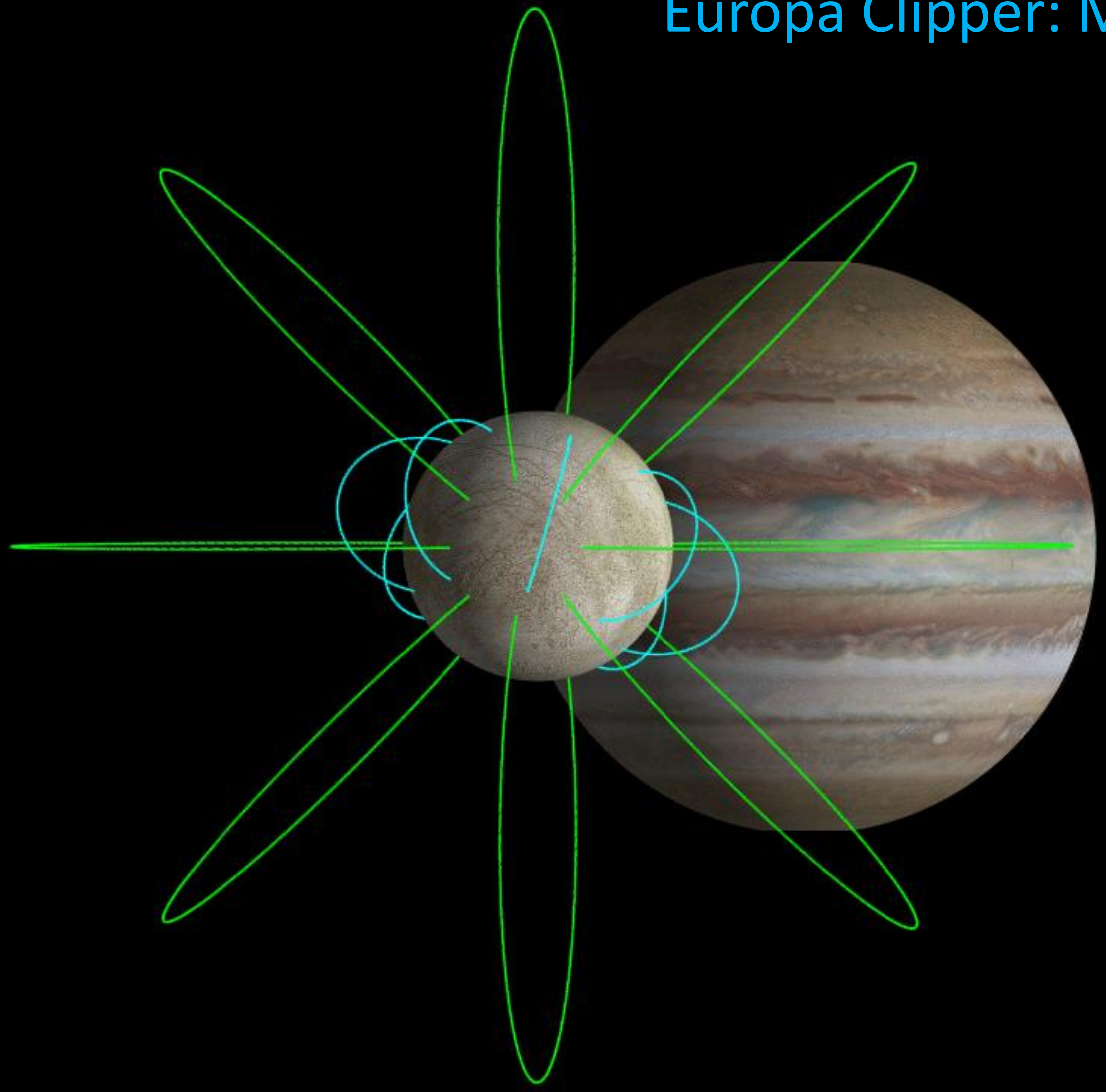
Europa E14 Pass

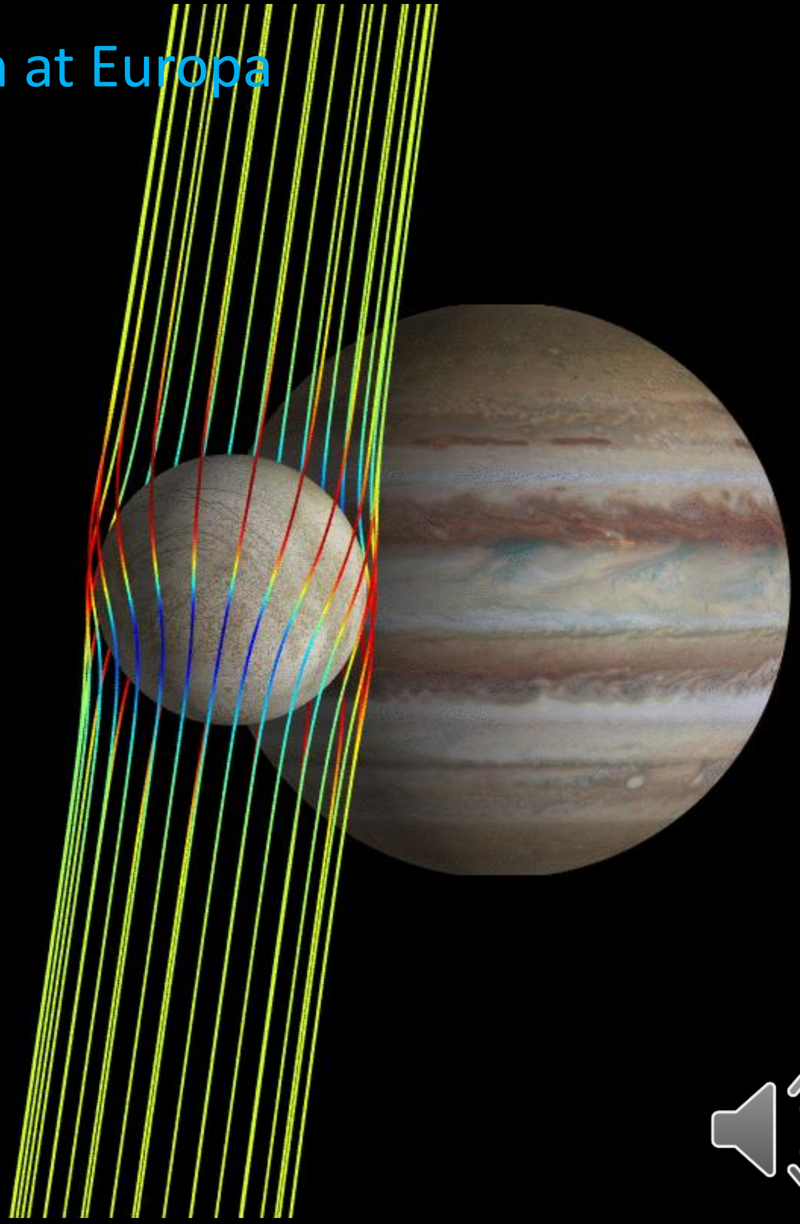


M.G. Kivelson, et al., Europa's Magnetic Signature: Report from Galileo's Pass on Dec. 1996, *Science*, 276, (1997).
M.G. Kivelson, et al., "Europa and Callisto: Induced or intrinsic fields in a periodically varying plasma env.", *J. Geophys. Res.*, 104, pp: 4609-4625, (1999).
C. Zimmer, at al., "Subsurface Oceans on Europa and Callisto: Constraints from Galileo Magnetometer Observations", *Icarus*, 147, 329–347 (2000).
K.K. Khurana, et al., "Searching for Liquid Water in Europa by Using Surface Observatories", *Astrobiology*, 2, 1, pp: 93-103 (2002).
N. Schilling, et al., "Time-varying interaction of Europa with the Jovian magnetosphere", *Icarus*, 192, 41–55, (2007)
M. Seufert, J. Saur, F.M. Neubauer, "Multi-frequency electromagnetic sounding of the Galilean moons", Icarus 214 477–494 (2011)

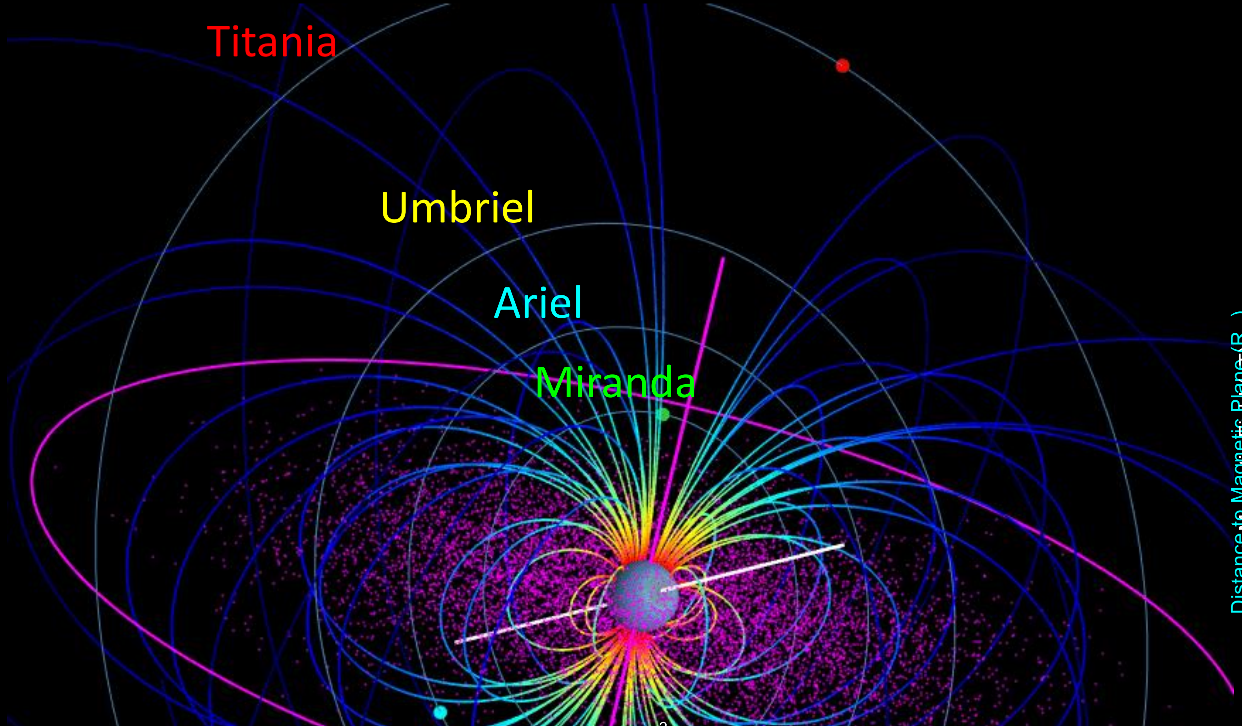
What Does Magnetic Induction Look Like?

Europa Clipper: Magnetic Induction at Europa



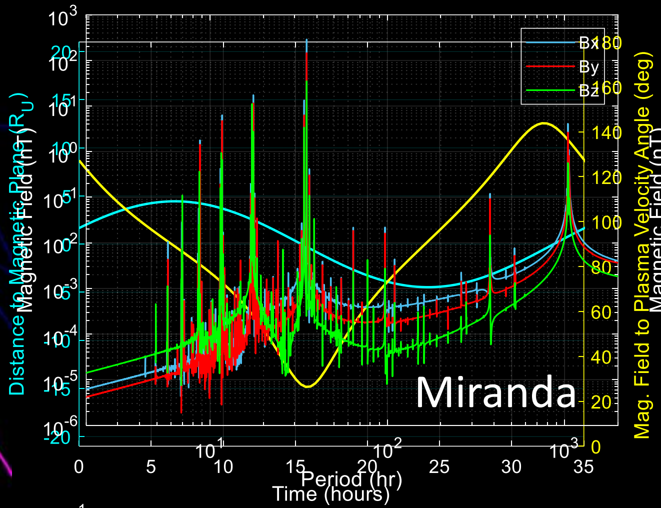


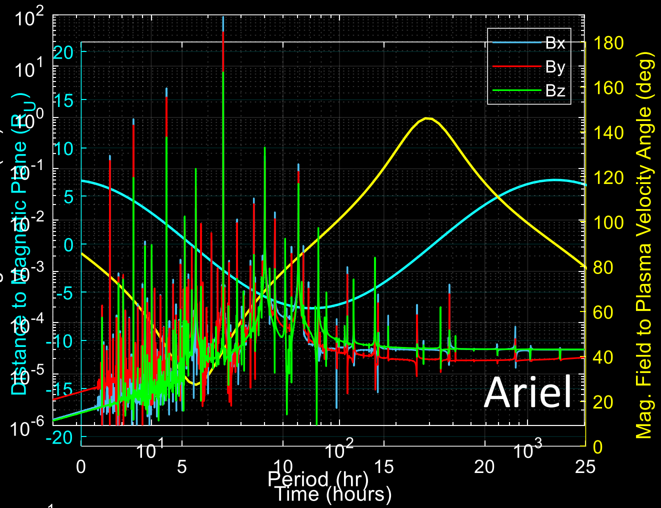
Uranus/Moon System has Favorable Geometry

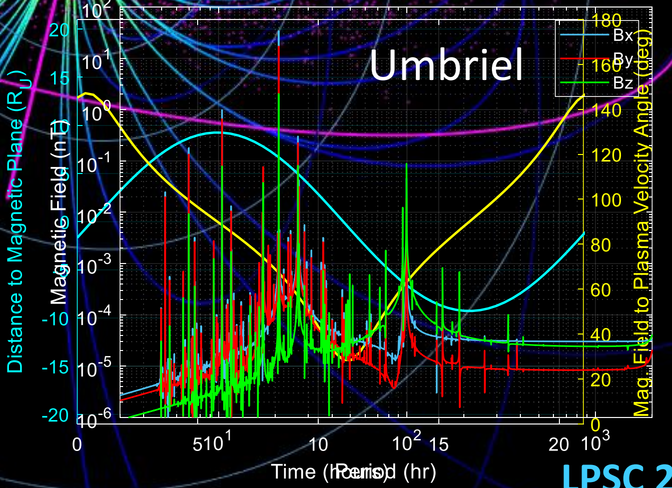


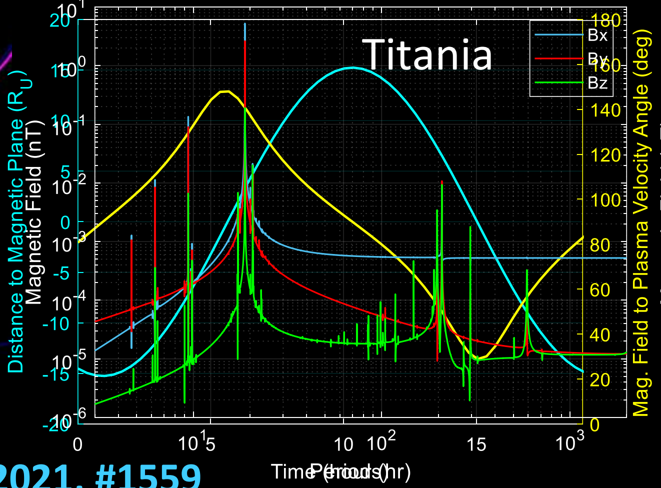
Geometry of Uranus / Moon system very favorable for:

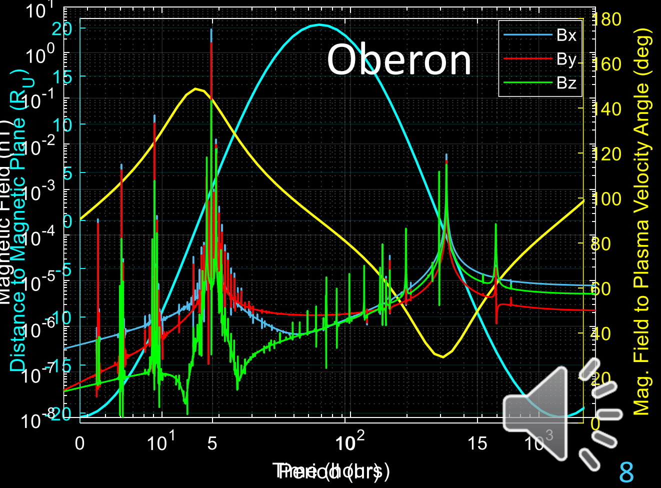
1. Generating strong time-varying fields at the Moons
2. Minimal plasma interaction effects











Corey J. Cochrane, JPL/CalTech

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Why Does Frequency Matter?

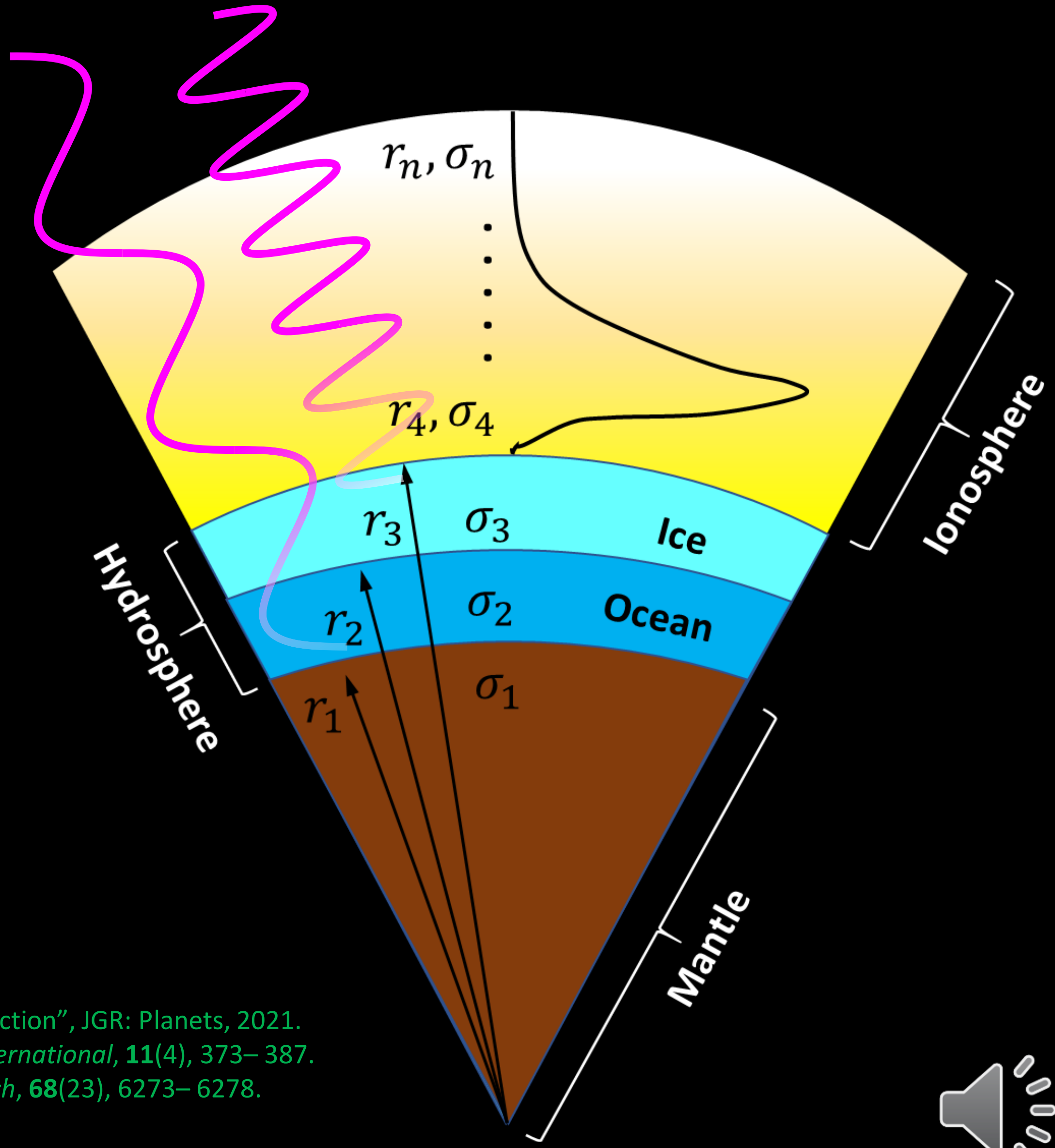
Large amplitude driving wave doesn't alone drive induction currents within the moon (if ocean present)

The magnetic waves will penetrate and drive electrical currents within a conductor at a depth in accordance to its skin depth

$$J = J_s e^{-d/\delta}$$

$$\delta = \sqrt{2/\omega\mu\sigma}$$

J_s = Surface current density
δ = depth when *J drops to 1/e (37%)*
ω = angular frequency
σ = conductivity of conductor
μ = permeability of conductor



Skin depth is inversely proportional to conductance and frequency

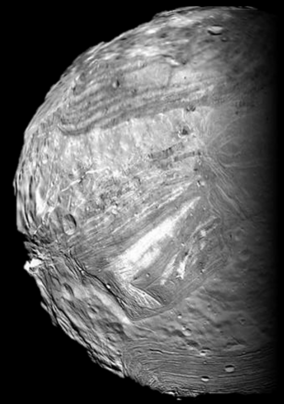
The higher the conductance and the higher the frequency, the less the wave will penetrate the conductor

Long waves are sensitive to deeper layers in the interior

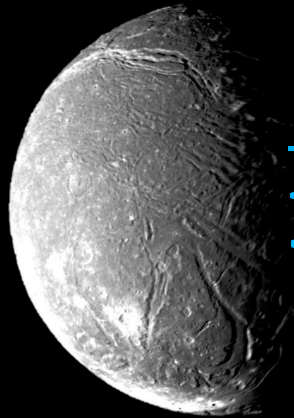
S. Vance, et. al, "Magnetic Induction Responses of Jupiter's Ocean Moons Including Effects from Adiabatic Convection", JGR: Planets, 2021.
Srivastava, S. P. (1966). Theory of the magnetotelluric method for a spherical conductor. *Geophysical Journal International*, **11**(4), 373– 387.
Eckhardt, D. H. (1963). Geomagnetic induction in a concentrically stratified earth. *Journal of Geophysical Research*, **68**(23), 6273– 6278.

Interior Complex Response Function

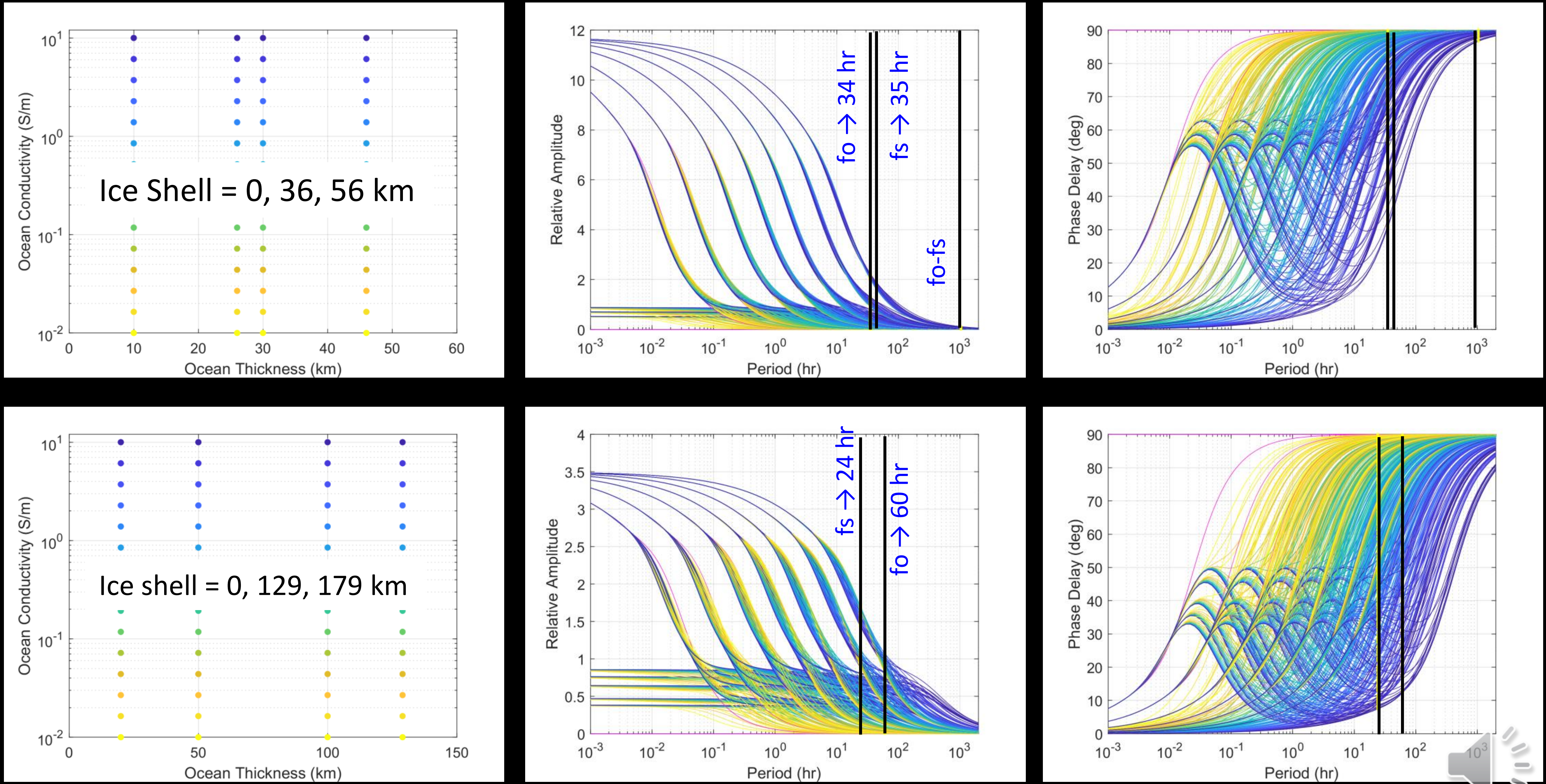
Ocean Conductivity vs Thickness | Amplitude Response | Phase Response



Miranda



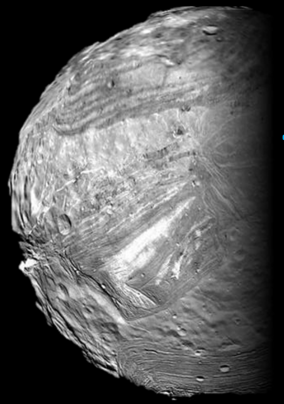
Ariel

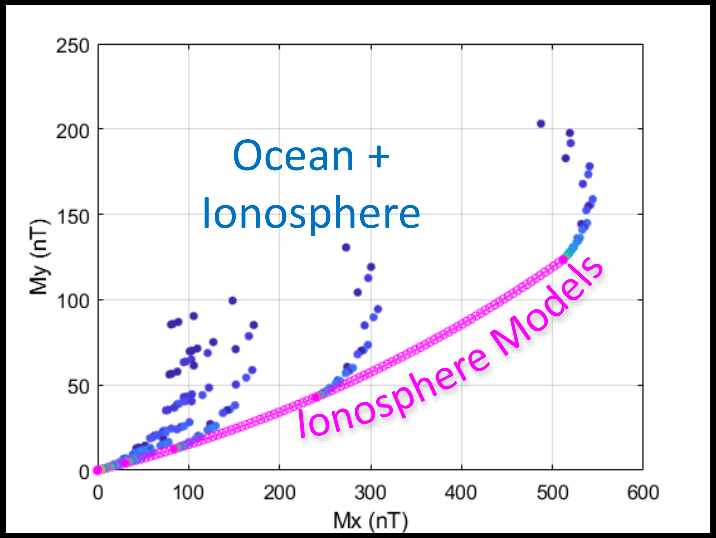


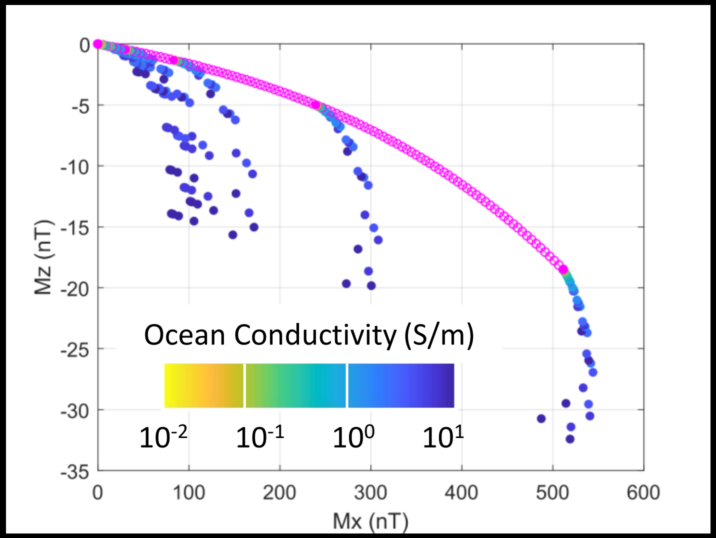
Magnetic Separation of Model Classes

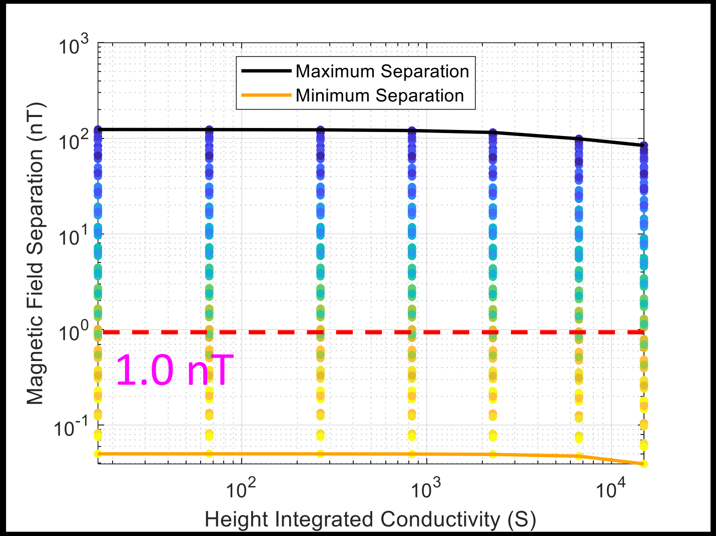
Total Mag. Moment (Mx/My) | Total Mag. Moment (Mx/Mz) | Separation Distance

Miranda









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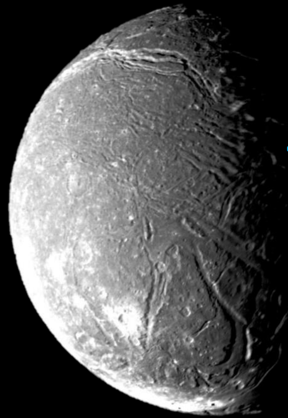

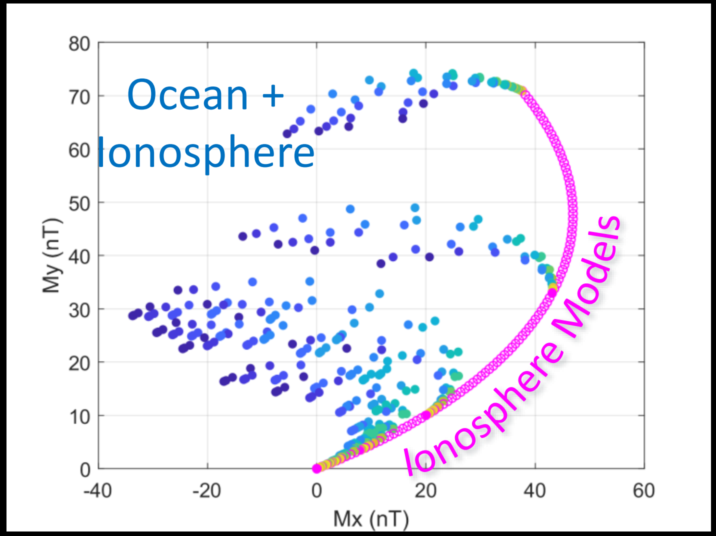

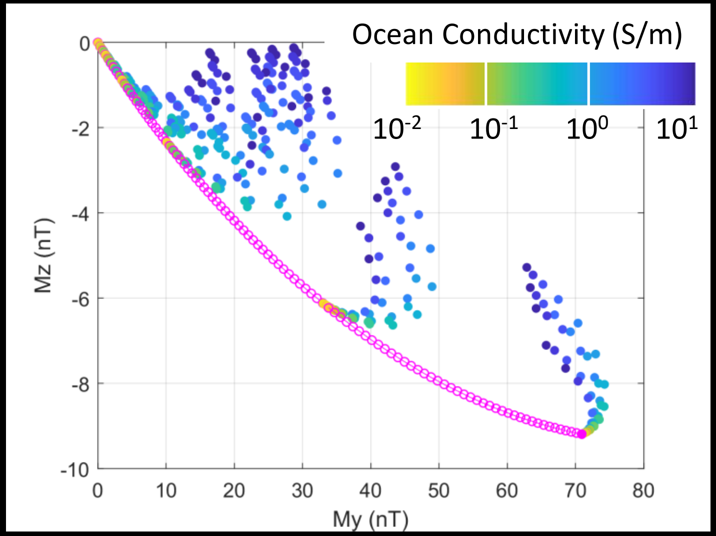

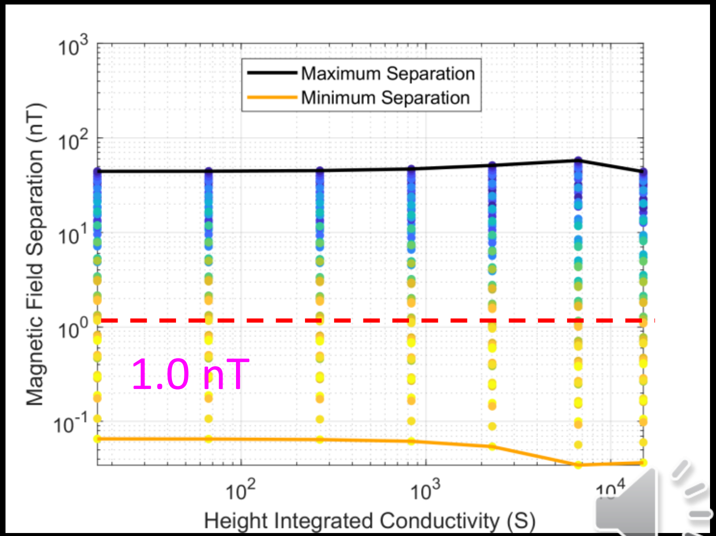

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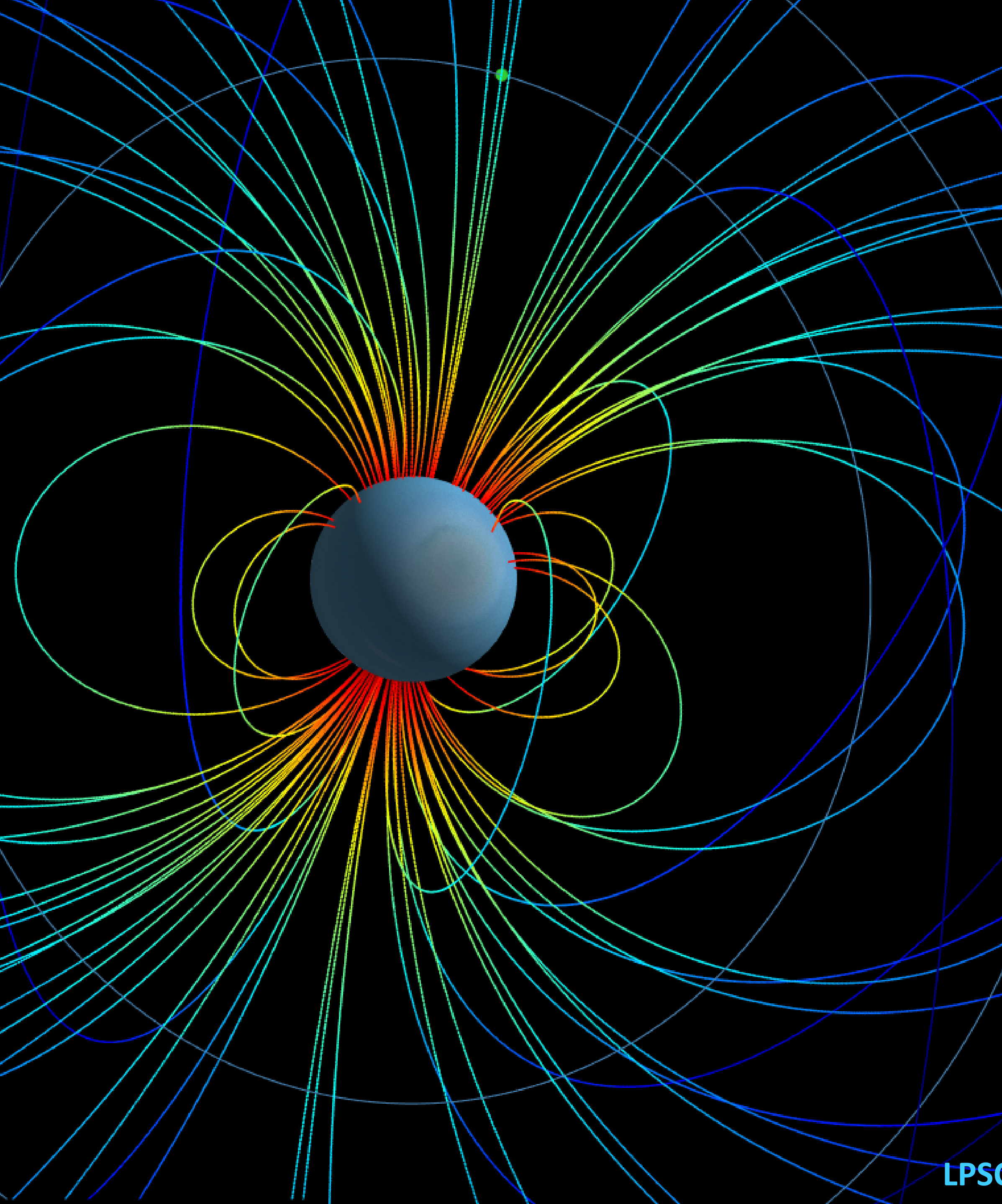
Summary and Future Work

Summary

- Moons of Uranus have the ideal conditions for magnetic induction investigation
    - Experience strong time-varying fields from Uranus
    - Complicated geometry is favorable for minimizing plasma induced effects
- Interior and ionosphere forward modeling approach allows for
    - determination of which models are actually detectable
    - applications for ocean detection on a single pass and potential ocean characterization

Future Work

- Assess magnetic separation at all phases of Uranus's magnetic field
- Develop additional models with increased parameter space
- Use existing trajectories developed by JPL to determine how well the ocean parameters can be recovered.



Thank you!

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For further information or questions, don't hesitate to contact me by email:

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